

Identification of an Optimal Range for Electric Vehicles for Different Charging Technologies

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Summary

This paper presents a method to analyze the relation between a vehicle's range, its chargings and its usage. The method includes a formalized description of charging rules, which depends on the application. An optimal range can be determined by counting the number of chargings and improper remaining ranges.

The results show that fast charging can improve the convenience for electric vehicles. Particularly when charging is not possible during the usage, fast charging is beneficial. Charging technologies like inductive or autonomous charging, which ease the start of a charging, are favorable with cars when chargings occur often and without fixed charging time windows (e.g. free floating car sharing).

Keywords: BEV, Range, Wireless charging, Fast charge, Autonomous

1 Introduction

Disadvantages in range and long charging times have hindered the breakthrough of electric vehicles (EV) because many private customers claim high flexibility and very short charging times for long distance trips. However, commercial vehicles are often used in urban areas with very regular patterns and the daily trip distance varies only slightly.

With rising sales numbers, an optimized vehicle range becomes crucial to improve costs and benefits for commercial customers. This raises the question as to which range a car should have for specific use cases in order to fulfill its ride distances without wasting installed battery capacity. A first survey on this issue was published by Schwartz [1] in 1977, using statistical data of American customers. Recent scientific investigations to answer this question have been undertaken in [2], [3] and [4].

The range of an EV has consequences on its usefulness and its costs. If the driver starts a charging, or the vehicle reaches a remaining range which is insufficient for the next ride, usefulness decreases. Hence, these are situations which need to be minimized. The smaller the battery the more often charging is necessary and an improper range is more likely to occur. The opposing trends of a smaller battery and higher charging frequency thus lead to an optimal range. The optimal range of an EV depends not only on the usage of the vehicle but also on the availability of charging stations, the charging technology and the recharging time.

This paper presents a novel methodology for vehicle development in an early stage to identify a cost-optimal range specification for EVs for use cases with regular and predictable usage patterns. Therefore, a usage model is developed that introduces rule-based charging. Different charging technologies (e.g. inductive charging, fast charging) are evaluated for two different charging scenarios. The first corresponds to the vehicle usage in shift operation. This means charging is done during lunch breaks and at night time. The second scenario matches to the charging of EVs in free floating car sharing fleets. Those vehicles are charged only below a certain remaining range, independent of time of day.

The methodology is examined on data of cars in the field of human health centers in Germany. Cars in this field are operated only within city or town borders. Long distance rides do not occur. The data stem from an acquisition of driving profiles in commercial traffic [5].

The paper is structured as follows: Chapter 2 gives an overview of current and future charging technologies. In Chapter 3 the modeling of usage behavior is explained, and the details of the vehicle and climate data are given in Chapter 4. The cost estimation and the assumptions are shown in Chapter 5. Chapter 6 gives an insight in the underlying usage scenario, which is followed by the results of the range estimation and parameter variations. Finally, concluding remarks are given.

2 Charging Technologies

Today's EVs are usually equipped with cable-based charging technology. Therefore, a number of protocol standards, connectors, and power supplies are established. Standard IEC 61851 defines general properties and low level communication. The electrical and geometric properties of the connectors are defined in IEC 62196. The power supply to the EV can be AC or DC.

AC charging is used for rather low power with a maximum power of 22 kW in star connection at a voltage level of 250 V/480 V. Single phase charging power is generally around 3 kW. In the North American market the Type 1 connector is commonly used while European countries established the Type 2 connectors.

Usually, the cable for AC charging has no fixed connection to the charging station or to the EV, so the cable must be transported in the vehicle and the customer has to handle the cable at every start and end of charging.

For fast charging, the DC technology with up to 240 kW is preferred because heavy power electronics are positioned in the charging station. This method uses the Type 3 connector and the cable is mounted at the charging station, which makes it easier to start and stop the charging process. When fast charging is used, the maximum power is not only restricted by the used cable and charging station, but also by the size of the battery because the power-to-energy ratio is limited.

An entirely different charging method is inductive charging, where a primary coil is placed in the ground of a parking place and the secondary coil is installed in the EV. Energy is transferred by high frequency electromagnetic fields. Thus, no mechanical connection between the charging device and the EV is necessary and a high automation of the charging process is possible. A drawback of the technology is that the driver needs to park exactly within a tolerance of few centimeters above the primary coil. Therefore, position assistance systems are made available [6]. This technology is not yet implemented in series production of EVs but it is promising to reduce the dependency on weather at unsheltered charging stations and to improve the convenience of EVs.

Furthermore, inductive charging could be combined with automated valet parking, which is in development by manufacturers and suppliers [7]. This decouples charging almost entirely from human interaction and fully automated parking assistance will be able to park and start the charging by itself.

In this paper four charging technologies are considered:

- Conventional cable-based AC charging with 3kW
- Cable-based fast DC charging with 20kW
- Inductive charging with manual parking
- Inductive charging with fully automated parking

The costs per charging are explained in Chapter 5.

3 Modeling Usage Behavior

Modeling the usage behavior of an EV combines data on rides and subsequent rule-based chargings. Using driver logbooks containing the distances and times of the rides of combustion engine cars [5], chargings need to be included in realistic patterns. Therefore, charging rules are established.

The decision on whether a charging is started depends on various factors. A formalized way to express these factors and to decide whether a charging is started can be done by setting up charging rules. For every factor a binary variable is introduced and the charging condition is either true or not, which is shown in the

equations (1) and (2) for the factors “remaining range” and “time of the day”. For example, if the remaining range is below a threshold ξ the logical value C_{Range} is 1, otherwise it is zero.

$$C_{Range} = \begin{cases} 0, & \text{if remaining range} > \xi \\ 1, & \text{if remaining range} \leq \xi \end{cases} \quad (1)$$

$$C_{time} = \begin{cases} 1, & \text{if } t \in [\text{charge time}] \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

The time-dependent factor C_{time} becomes active when the time of the day t is within the daily charging window. The factors C_{Range} and C_{time} are connected by logic operators to C_{charge} which indicates if starting a charging is possible. Charging starts automatically if the car is already parked. If a ride occurs during the charge, charging is interrupted and restarted if the end of the ride lies in the charging window.

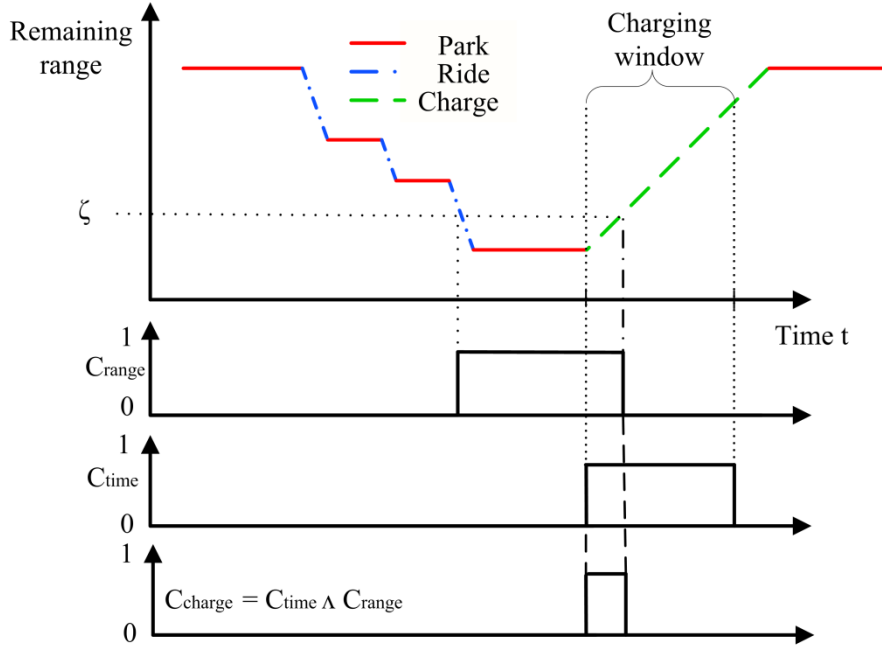


Figure1: Schematic example of charging rules

The exact formulation of the charging rule depends on the considered use case. An example is shown in Figure 1. As a simplification it is assumed that charging can take place every time it is necessary. Thus, the charging infrastructure is not considered in this paper.

Measures to benchmark the scenarios are the number of chargings and the number of improper remaining ranges. An improper remaining range (in the following: improper range) occurs if the remaining range after a ride is below 5km. It is assumed that a reliable assistance system warns the drive in a timely manner to start an unscheduled recharging.

4 Vehicle and Climate Data

For every range a battery capacity can be estimated. Thus, the costs for the battery pack can be calculated. The relation between range and battery capacity is defined by the energy consumption per distance. The consumption is influenced by various parameters such as climate or the typical driving cycle of the use case. Also, range itself influences the energy consumption as shown in Figure 2 because of an increased battery mass. The relationship is determined by simulation of a driving cycle representative for traffic in Germany with a Smart ED drive train model as explained in [8]. The energy content of the battery is varied by parallelized cells.

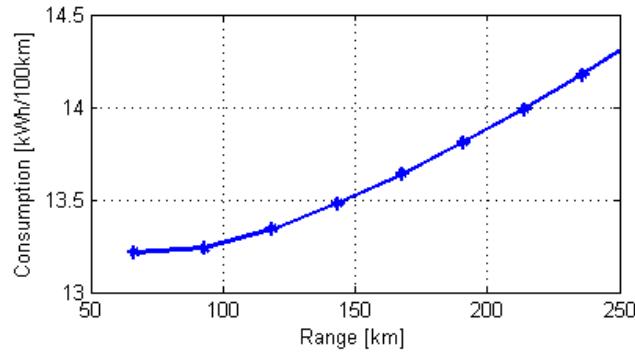


Figure 2: Energy consumption for different vehicle ranges

Ambient temperature has a large impact on the range of the vehicle because air conditioning requires much energy, as can be seen in Figure 3 which shows the average A/C power from a testing series on the Stuttgart driving circuit, presented in [9].

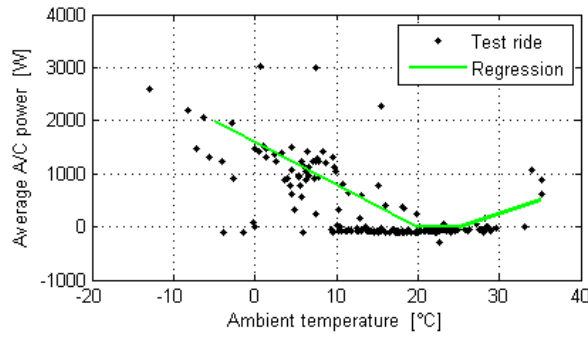


Figure 3: Measured A/C power over ambient temperature

For this analysis the monthly average ambient temperature of Stuttgart over the course of a year is used to determine the necessary A/C power. Together with the consumption curve in Figure 2, the required energy for the rides is calculated. The term *range* in this paper is always defined as the base range without air conditioning. This means that an average ride of 10 km (same cycle as above, average velocity: 50 km/h) in a vehicle with a range of 140 km consumes 1.35 kWh without air conditioning. At an ambient temperature of 0°C the A/C needs an additional 0.31 kWh, which is added on the range, and the consumed range is thus 12.3 km.

5 Cost Estimation

A plausible cost estimate for the different technologies is essential for reliable results of the model. The range-related costs of the EV (i.e. battery) and the cost due to the time loss for charging are used. Costs for the charging infrastructure are not taken into account.

The costs for the battery pack are assumed to be linear to its energy content. To compare battery costs with the usage-depending costs, the battery costs are set to 300 €/kWh and an average holding period of 5 years for the cars is used for the following scenario. The resale value of the battery is not taken into account. An estimation of future prices depends on the development of the costs of new batteries and various other factors and is thus uncertain. Studies also show that the benefit for the TCO is indicated to be only in the range of 1-3 % [10].

The costs for starting and for an improper range depend on the used charging technology. A study with test persons was carried out to assess the different charging technologies [11]. Mostly unexperienced customers performed the starting of inductive and cable based charging and completed a questionnaire afterwards. Also the time to start the process was taken. First results show that inductive charging is performed slightly

faster than cable-based charging, even for customers with no experience with the positioning interface. Additionally, cable-based charging needs time to unplug the cable. The times to start and stop the process for inductive, cable-based and fast charging in Table 1 are derived from the study, and for cable-based and fast charging an estimated time to end the charging is added. For autonomous charging the time to start and stop the process is estimated.

The costs to start and end a single charging are calculated by the required time to start and stop the process multiplied by the hourly wage:

$$Cost_{chg,spec} = t_{startEndChrg} \cdot wage_{hourly} \quad (3)$$

If an improper range occurs, it is assumed that the driver is informed in a timely manner by an assistance system. In this way a charging station can be reached in time. The costs are calculated as follows:

$$Cost_{improp\ range,spec} = (30\ min + t_{Fullcharge}) \cdot wage_{hourly} \quad (4)$$

The calculation contains the time to charge the battery fully. Also, thirty minutes are allotted as additional time to travel to a charging station. This time is multiplied by an estimated hourly wage of 15 €.

The values for the times and costs are shown in Table 1. Fast charging does not change charging costs, since the starting procedure stays the same, whereas the costs for an improper range become much cheaper, because spontaneous charging is less time consuming. Inductive and autonomous charging reduces the charging costs while the costs for an improper range stay the same.

Table 1: Times and costs for different charging technologies

	Cable-based 3kW	Fast charging	Inductive charging	Autonomous charging
Time to start and stop the process [s]	220	220	100	10
$Cost_{chg,spec}$ [€]	0,92	0,92	0,42	0,04
$t_{Fullcharge}$ [h]	6,0	1,0	6,0	6,0
$Cost_{improp\ range,spec}$ [€]	97,50	22,50	97,50	97,50

The usage dependent costs for charging and improper remaining ranges can be interpreted as a measure for convenience, because they are proportional to the time the driver is occupied with charging. The higher the charging expenditure, the less comfortable is the technology or range.

6 Usage Scenarios

6.1 Ride Data

The usage data were acquired in [5]. For our analysis the data of human health centers, like “meals on wheels” and service for out-patients, are used. Cars in this field are usually operated only within city or town borders. Cars with outlying long rides above 100 km are removed from the data. Mean distance per ride of the remaining 79 cars is 3.3 km. The data logging per car is recorded for 3 weeks. Figure 4 shows the distribution of distance per trip and distance per day. The distance per trip is usually very short with a maximum trip distance of 90 km; the daily driven distances are much longer with up to 200 km (on days with rides).

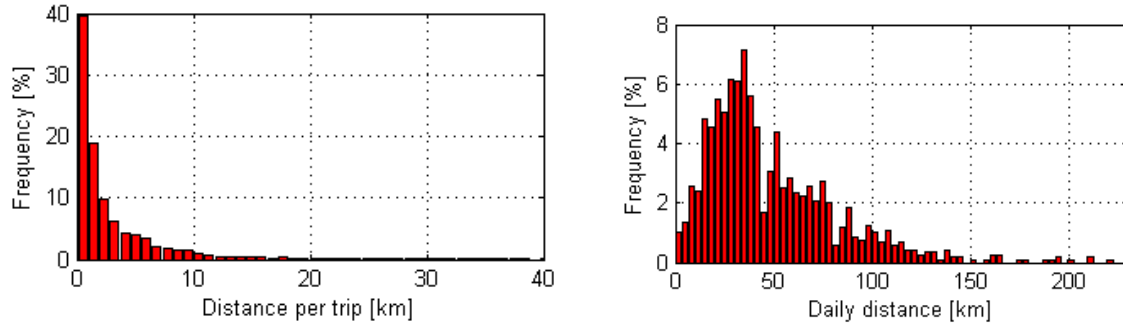


Figure 4: Distance of the data per trip and per day

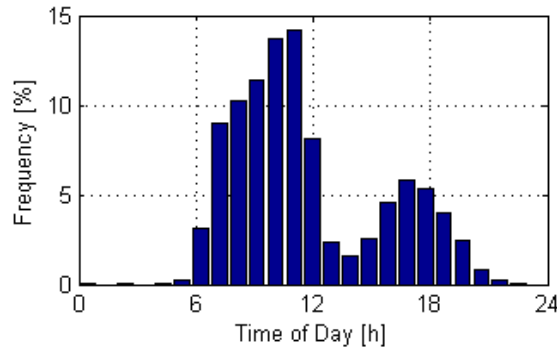


Figure 5: Trip start at time of day

The average usage over the course of a day is shown in Figure 5. The vehicles' highest usage is in the morning through 1pm, and in the afternoon after 3pm. Only few rides occur during the 2 o'clock hour, which indicates that drivers take their lunch break.

6.2 Charging rules

The theoretical expressions of the charging rules are explained in Chapter 3. For the shift operation charging rule it is arranged so that charging is possible at night between 8 pm and 5 am, and in the afternoon between 2 pm and 3 pm. This charging rule matches to the use case explained above. A charging C_{charge} is only performed when the time of day lies within the defined time slot and the remaining range is below the charging threshold:

$$C_{charge} = C_{Range} \wedge C_{time} \quad (5)$$

This threshold is not fixed, but an optimal threshold is determined for every tested vehicle range.

The charging rule for car sharing can be expressed as:

$$C_{charge} = C_{Range} \quad (6)$$

Hence, the charging is not time dependent anymore and can occur at any time of the day. The only requirement for charging is a remaining range below the charging threshold. This is a common method in free floating car sharing fleets. The optimal charging threshold is also range dependent.

7 Range Estimation for Different Scenarios

7.1 Charging Rule for Shift Operation

This section shows the results for the charging rule for shift operation according to equation (5).

7.1.1 Comparison of Charging Expenditure

In the first analysis, the charging expenditure for the different charging technologies are investigated at a fixed range of 140 km. The charging rules from Equation (5) are applied and the charging threshold is varied to find the cost optimal threshold ξ_{opt} for each charging technology. The results are shown in Table 2. All costs are noted as costs per year. The charging expenditure describing the effort for the charging process are the highest for cable-based charging with 1064 €/a. Additionally, high charging expenditures result from inductive charging and autonomous charging, because of high total costs for improper range. At fast charging the costs for improper ranges are much lower, which leads to lower charging expenditures.

The optimal threshold is lower at fast charging because improper range is cheap. Autonomous charging is cheap, so the optimal threshold is high.

Table 2: Usage depending costs for different charging technologies at a vehicle range of 140 km and shift operation

	Cable-based 3kW	Fast charging	Inductive charging	Autonomous charging
Charging expenditures [€] ($Cost_{chrg} + Cost_{imprRng}$)	1064	391	827	606
$Cost_{chrg}$ [€]	412	229	216	23
$Cost_{imprRng}$ [€]	652	162	611	583
Optimal charging threshold ξ_{opt}	110 km	90 km	120 km	130 km

7.1.2 Range Optimization

The result of the optimization for regular cable-based charging is shown in Figure 6, which shows the costs per year and vehicle. The optimal range is around 170 km. The most expensive share is the battery. As can be seen, usage dependent charging expenditures rise with smaller range. In particular, total costs for improper range depend strongly on the range, whereas costs for charging are nearly constant because of the restricting charging times. The frequency of chargings and the frequency of improper range in percent of the total rides are shown in Figure 7.

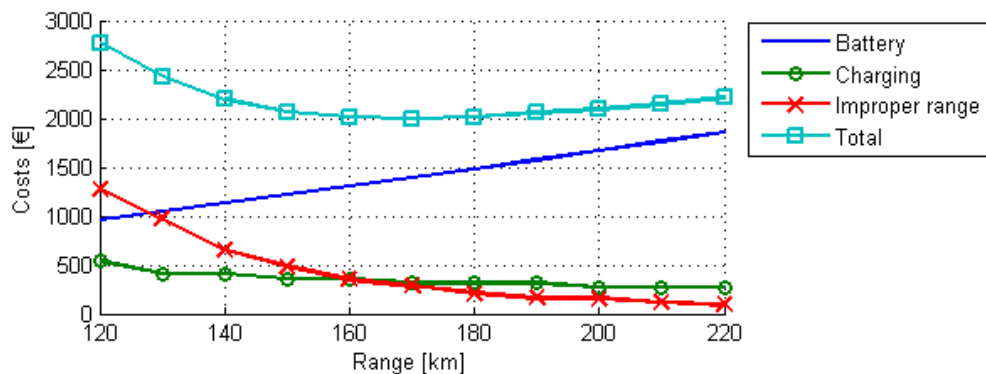


Figure 6: Costs over range for cable based charging

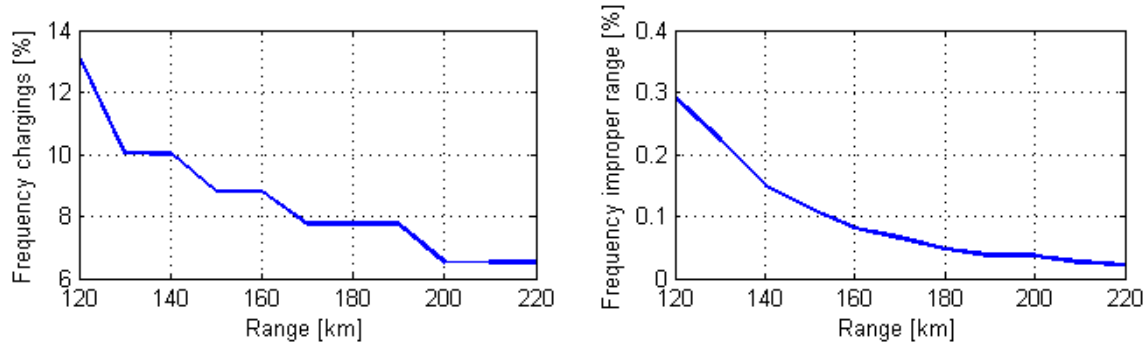


Figure 7: Frequency of chargings and improper range for cable-based charging

All results of the different charging technologies are shown in Table 3. It is evident that the optimal range does not defer extremely for the different technologies. Fast charging leads to the lowest optimal range with 130 km, whilst cable-based and inductive charging lead to the same optimal range of 170 km. Autonomous charging has an optimal range of 160 km. The battery sizes are derived from the optimal range with the graph from Figure 2.

Cable-based and inductive charging show similar results for the number of chargings and the number of improper ranges. Also the optimal charging threshold ξ_{opt} hardly varies for the two technologies. Fast charging ξ_{opt} is lower than for the other charging methods, which leads to a higher number of improper ranges. In this model, fast charging technology thus leads to more spontaneous chargings, because compared to the 3 kW charging it is less expensive and time consuming. For autonomous charging, the costs to start a charging are very cheap which leads to a high ξ_{opt} and the cars are charged almost at every possible charging time. This leads to a high charging frequency.

The charging expenditures differ from those in section 7.1.1 because of different vehicle ranges. For inductive and especially for autonomous charging the charging expenditures are low, while for fast charging it becomes slightly more expensive. In total, fast charging leads to the smallest range (and thus: battery) and is the cheapest, if costs for the battery and charging expenditures are considered.

Table 3: Range optimization of the charging rule for shift operation

	Cable-based 3kW	Fast charging	Inductive charging	Autonomous charging
Optimal range [km]	170	130	170	160
Costs battery [€]	1393	1046	1393	1304
Battery size [kWh]	23.2	17.4	23.2	21.7
Charging expenditures [€] ($Cost_{chrg} + Cost_{imprRng}$)	602	456	409	326
$Cost_{chrg}$ [€]	318	270	165	23
$Cost_{imprRng}$ [€]	284	186	244	303
Charging [%]	7.6	6.6	8.8	13.1
Improper range [%]	0.065	0.181	0.056	0.070
Optimal charging threshold ξ_{opt}	120 km	90 km	130 km	150 km

The investigation shows that the optimal range is lower with fast charging than with the other charging technologies. This is because fast chargings reduce time effort and thus costs of unscheduled chargings. Inductive charging does not change optimal range compared to cable-based charging, because chargings do not occur very often due to the charging rules. In addition, autonomous charging does not lead to a significant smaller optimal range for the same reason.

7.2 Charging Rule for Car Sharing Usage

For the investigation of the charging rule for Car Sharing, equation (6) is used. To analyze the impact of the charging rule, the same ride data are used.

7.2.1 Charging Expenditures

The range is again fixed to 140 km to investigate the charging expenditures for the different charging technologies for vehicles with equal ranges.

Since charging is possible throughout the entire day, the number of charging rises and the number of improper ranges decreases. The results in Table 4 show that charging expenditures rise for cable-based and fast charging. Inductive charging and autonomous charging become cheaper.

Table 4: Usage depending costs of the charging rule for car sharing at a range of 140km

	Cable-based 3kW	Fast charging	Inductive charging	Autonomous charging
Charging expenditures [€] ($Cost_{chrg} + Cost_{imprRng}$)	1271	439	692	154
$Cost_{chrg}$ [€]	1065	384	486	71
$Cost_{imprRng}$ [€]	206	55	206	83
Optimal charging threshold ξ_{opt}	90 km	60 km	90 km	120 km

7.2.2 Optimal Range

The results of the optimized range for the different charging technologies are shown in Table 5. Although the optimal range is slightly higher, the charging expenditures for autonomous charging are much lower than for fast charging. In comparison to the charging rule for shift operation the results show that autonomous charging delivers the lowest charging expenditures and a small optimal range.

Thus, an important factor for comparing different charging technologies is not only the usage in terms of ride distribution, but also the charging behavior in the application. For usages with fixed operating times, fast charging leads to smaller optimal ranges. For use cases where time independent charging is possible (e.g. car sharing), autonomous charging is preferable.

In general, the determined optimal ranges in this section are smaller than those in Section 7.1, which follows from a higher possible charging frequency.

Table 5: Range optimization of the charging rule for car sharing

	Cable-based 3kW	Fast charging	Inductive charging	Autonomous charging
Optimal range [km]	160	110	140	120
Costs battery [€]	1304	878	1131	961
Battery size [kWh]	21.7	14.6	18.9	16.0
Charging expenditures [€] ($Cost_{chrg} + Cost_{imprRng}$)	1047	556	692	275
$Cost_{chrg}$ [€]	839	455	486	91
$Cost_{imprRng}$ [€]	208	101	206	184
Charging [%]	20.4%	11.1%	25.9%	50.7%
Improper range [%]	0.048%	0.100%	0.047%	0.042%
Optimal charging threshold ξ_{opt}	90 km	50 km	90 km	110 km

8 Conclusion

This paper presents a method to analyze the relation between a vehicle's range, its chargings and its usage. The method includes a formalized description of charging rules, which depend on the use case. By counting the number of chargings and improper remaining ranges after rides an optimal range can be determined. It can be used to analyze usage patterns and to derive optimal vehicle ranges under given cost and charging constraints.

The results show the consequences on the optimal range and time consumption for charging of different charging technologies. For the charging rule for shift operation with two charging times per day, fast charging improves charging expenditures and shows the smallest optimal range. Inductive charging is not very beneficial compared to cable-based charging. The optimal range of the vehicle is the same and the charging expenditures are not much lower. Autonomous charging shows the lowest charging expenditures for the optimized range. The optimal vehicle range for this example is between 130 km and 170 km.

In the second example the car sharing charging rule depends on the remaining range threshold only. For this scenario inductive charging becomes more advantageous compared to cable-based technology. Autonomous charging has the lowest charging expenditures for the fixed and the optimized range.

This leads to the conclusion that charging technologies like inductive or autonomous charging, which ease the start of a charging, are favorable with cars where chargings occur often and without fixed charging times (e.g. for car sharing). If EVs are used in applications where charging during usage is not possible, fast charging can help to improve the usage possibilities because the quicker an unplanned recharge is, the more similar it becomes to established refueling of combustion engine vehicles from a customer perspective.

Further investigations should focus on the influence of charging infrastructure. Other vehicle applications should also be examined by clustering to appropriate segmentations.

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